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Improved Meteorological Measurements from Buoys and Ships (IMET): Preliminary Analysis of Solar Radiation and Motion Data from IMET Test Buoy.

by

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Technical Report

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Abstract

Data are analyzed from a test buoy equipped with a motion sensor (Hippy) and two different pyranometers in order to understand and quantify motion induced errors in meteorological data. The Hippy measures pitch, roll, heave and acceleration of the buoy. Probability density functions and spectra of buoy motion and insolation are constructed and discussed.

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1 Introduction and Motivation

Some of the error in meteorological measurements made at sea is associated with the motion of those sensors and of the moving platform, ship or buoy on which they are mounted. In an attempt to better understand and quantify this error a buoy was fitted with a motion sensor and two different pyranometers.

Pyranometers measure the vertical flux of total direct solar and diffuse sky radiation integrated over a hemisphere. Because a pyranometer views a complete hemisphere, tilts in the sensor from horizontal will lead to erroneous values in measured irradiance. With a simple model, Katsaros and DeVault (1986) estimate errors in insolation values observed on buoys may be in excess of 20% due to rocking caused by wave action and preferential tilt of the buoy with respect to solar zenith and azimuth. The magnitudes of these errors are a function of tilt angle and tilt direction, latitude, time of day, time of year, and cloudiness.

This represents the first step in our attempt to quantify and reduce errors due to platform motion. To date, the buoy has been deployed only briefly. We plan next to collect longer time series of buoy motion under different conditions, to collect records of ship motion, and to investigate the effectiveness of gimbals in reduced motion induced error.

This report documents the installation of the Hippy on the buoy, the sensors, and the data acquisition system. It also presents data from the first deployment of the buoy. This work is done as part of the NSF-funded program to make Improved Meteorological Measurements from Buoys and Ships (IMET).

2 Description of IMET Test Buoy and Sensors

The IMET Test Buoy (Fig. 1) was a 3 meter discus buoy commonly used by the Woods Hole Oceanographic Institution (WHOI). The buoy was deployed at

1911 UTC on 17 January 1989 and recovered the following day at 1445 UTC. The location was at the WHOI Buoy Farm off the coast of Rhode Island at 41°16′N, 71°02′W. Water depth was approximately 39 meters. The ship used for deployment and recovery was the *R/V Endeavor* (EN-189).

The Datawell 120-B Hippy housing is cylindrical in shape measuring 60.6 cm in diameter and 80.8 cm in height and weighs 120 kg. The Hippy was placed inside the well slightly off center of the buoy. The two pyranometers were placed on top of the tripod superstructure approximately 3 m high from the buoy deck which had an unobstructed view of the sky.

Power was provided by two 12 volt lead-acid batteries located in a water tight, vented box on the well cover. The LOPACS data logger was housed in an aluminum pressure case that was mounted vertically on the deck of the buoy. Later versions of the buoy configuration will use a smaller Hippy and have the data logger and batteries located inside the well. An ARGOS transmitter was mounted on the buoy tripod and configured for position only for this test. A VHF transmitter was also installed to permit line of sight data transmission from the buoy to the ship for real time monitoring during the test.

The signal outputs of the Hippy are pitch, roll, heave, and vertical acceleration. An accelerometer is mounted on a gravity stabilized platform with a natural time period of 120 seconds.

The pitch is defined as the angle between the roll axis of the ship and the horizontal plane. The pitch is positive when the rear of the ship is lifted. Similarly, the roll is the angle between the pitch axis of a ship and the horizontal plane. The roll is positive when the port side of the ship is lifted. The acceleration is positive during upward acceleration and likewise the heave is positive when displacement from rest is upwards. Table 1 lists specifications of the Hippy.

Also included in the sensor package of this test buoy were two pyranometers. The first was an Eppley 8-48 Black and White Pyranometer. This sensor is a differential electroplated (copper-constantan) thermopile with the hot-junction receivers blackened and the cold-junction receivers whitened. The spectral response of the sensor is from 0.28 to 2.8 micrometers. The Schott WG7 glass dome that covers the thermopile is essentially transparent to this bandwith.

The second pyranometer was a Hollis MR-5 Silicon Cell Pyranometer. This silicon based sensor has an active band response of 0.4 to 1.2 micrometers but has been calibrated at the factory against thermal response pyranometers to effectively create a useful bandpass of 0.28 to 2.8 micrometers, essentially covering the entire range of the incoming solar spectrum. The MR-5 does not come with a protective glass dome like the Eppley 8-48. A summary of the factory specifications of both pyranometers is given in Table 2.

Both pyranometers were amplified by a precision low noise amplifier. This was necessary in order to raise the signal levels within the proper dynamic range of the acquisition system.

These two pyranometers were chosen for their different time constants. The Eppley has a time constant of 3 to 4 seconds while the Hollis a time constant that is less than 1 second. The intention is to quantify the errors against the time response and better parameterize a correction factor.

3 Data Acquisition System

The system used to acquire and store data is a specially designed low-power IBM PC compatible computer with optical disk storage facilities. During the deployment the system acquired data for a 15 minute cycle each hour. Signals from the Hippy and pyranometers were digitized with a 16-bit analog-to-digital converter at a 4 Hz rate. During the active cycle, data was stored in a RAM disk file. The file was transferred to the optical disk for permanent storage at each cycle's end. Ten cycles were successfully completed during the deployment.

The buoy was recovered prematurely because of a failure in the computer system watchdog circuit. The circuit is responsible for awakening the system each hour. The system, an IMET prototype, was reset and again functioned properly. However, due to the uncertainty of another failure, the buoy was subsequently recovered.

4 Weather and Wave Conditions

The general overall weather picture during the test may be described as fair. Skies were partly to mostly sunny for the 17 and 18 January with some scattered stratocumulus clouds being more predominant early on 17 January. This can be seen in Fig. 2 from insolation values taken at Woods Hole. Wind speeds were moderate at 10 to 15 m s^{-1} from the southwest at the buoy farm (Figs. 3 and 4). Wind speeds dropped during the evening hours and veered to have a more westerly component. By the second day the winds were more northwesterly but were relatively light (less than 5 m s^{-1}). Sea swell was generally observed to come from the southwest from 1.0 to 3.0 m on the first day to less than a meter by 18 January.

The barometric pressure changed little during the cruise. The pressure had dropped slightly (Fig. 5) but the overall changes were relatively small. Air temperatures (Fig. 6) changed very little ranging from 3.5 to 6.5°C. Sea surface temperatures also were relatively unremarkable (Fig. 7) ranging from 3 to 8°C.

5 Data Analysis

The mean, variance and standard deviation were computed for the pitch, roll, heave, acceleration and insolation for all data files (Table 3). The minima and maxima were also computed for each variable. A summary of these statistics can be seen in Tables 4–13.

For much of the time that the buoy was deployed, the range of the pitch and roll was on the order of 10 degrees. However, the mean pitch and roll were not zero as there was a slight tilt in the buoy due to the off-set from center of the Hippy, computer, and lead-acid batteries. The mean acceleration while the buoy was deployed was approximately 0.4 m s^{-2}. The mean insolation values were within several W m^{-2} between the Eppley and Hollis pyranometers.

Of the ten data files recorded, three 15-minute files contain useful insolation data. These are 20 and 21 UTC on 17 January and 13 UTC on 18 January. The time series plots of these insolation data can be seen in Figs. 8, 9 and 10, respectively. Insolation values recorded at Woods Hole (approximately 40 km away) are over plotted on these figures.

It is immediately apparent that the MR-5 has a much noisier signal over the 8-48. This is because the MR-5 time response, for all practical purposes, is nearly instantaneous, whereas the time response of the 8-48 is on the order of several seconds. Hence, as the buoy moves back and forth across the sun, the MR-5 can observe the large fluctuations in apparent incoming solar energy, while the 8-48 is much slower to respond. The objective is to relate the time response of these instruments to that of the buoy motion relative to the sun angle and determine, if possible, a quantitative correction.

Probability density functions (PDF) were computed for the pitch, roll, heave, and vertical acceleration. The pitch and roll (Figs. 11 and 12 respectively) show a large variance in the buoy early in the deployment (20 UTC) but was greatly reduced by the next day (13 UTC) when the sea state was much calmer. Winds were relatively strong when the buoy was first deployed and the sea state was moderately rough with swell of 1–2 m. However, by the next day the winds had decreased significantly and sea state was very near calm. The PDF's for buoy pitch and roll show significantly less rocking motion compared to that seen in the previous day.

The PDF's show heave (Fig. 13) up to ± 2.0 m at 20 UTC but was down to less than ± 1.0 m by the next day when sea state had calmed. The vertical acceleration (Fig. 14) also typifies the before and after scenarios.

Spectral analysis was performed on these variables. Spectra of the pitch is shown in Figs. 15 and 16 for 20 UTC and 13 UTC, respectively. The energy containing frequencies occur between 0.2 and 0.5 Hz, corresponding to wave periods of 2 to 5 seconds. Spectra of the roll are nearly identical to that of the pitch. The power drops for the spectra by 13 UTC on 18 January as the sea state calmed. The spectral peak had also shifted slightly towards the higher frequencies.

Heave spectra are shown in Fig. 17 and the acceleration spectra in Fig. 18 for 20 UTC on 17 January. A sharp peak exists for the heave at about 0.2 Hz. Most of the energy containing frequencies for the acceleration lie between 0.15 and 0.5 Hz. The spectral power for the lower frequencies is nearly nonexistent.

The spectra of the two pyranometers match up well from the lowest frequencies up to about 0.1 Hz. From 0.1 to 1 Hz the spectral powers of the two sensors are very much different. Fig. 19 shows the spectra of the two pyranometers for 20 UTC on 17 January. The Eppley spectra continues to decay whereas the Hollis spectra mimics the pitch/roll spectra. This is also again true for 13 UTC on 18 January (Fig. 20).

This information tells us that the Eppley 8-48 pyranometer has a time constant on the order of 10 seconds rather than the quoted 3 to 4 seconds. The Hollis pyranometer, on the other hand, mimics the pitch motion very well. It may be possible to correct for this error spectrally, much like that exhibited by Dugan *et al.* (1989).

6 Summary and Conclusions

The implications of this work go far beyond corrections for insolation data on buoys. Other sensors such as pyrgeometers, wind sensors, and rain gauges would also suffer the same ill affects of buoy motion. For instance, Dugan *et al.* (1989) correct wind data on a buoy spectrally using Hippy pitch, roll, and heave data.

There are several recommendations for improvements for future tests such as the one described here in this report. First, a compass included in the sensor package of the IMET test buoy would help determine the orientation of the buoy with respect to the sun position. This way, data obtained from the pyranometers from the buoy can be checked against the model by Katsaros and DeVault (1986). Second, a larger data set will be needed for such an exercise. When the IMET test buoy was deployed and for much of the deployment, skies were partially overcast with clouds. Clear sky conditions would be ideal to compare against the above mentioned model since it is based on clear sky conditions.

Two similar pyranometers should be tested with the Hippy. One pyranometer should be rigidly mounted to the superstructure of the buoy while the second pyranometer mounted on a gimbaled platform. This may also be done on a ship. With this type of arrangement, a systematic error analysis may be conducted and, hopefully, a parameterization scheme that may allow us to minimize the errors associated with platform induced motions.

Acknowledgements

The authors wish to thank the Captain and crew of the R/V *Endeavor* and the WHOI Buoy Group for their assistance in deploying and recovering the discus buoy. The authors also wish to thank Barbara Graffron for reviewing this report and making helpful suggestions.

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Dugan, J. P., S. L. Panichas, W. D. Morris, and K. C. Vierra, 1989. Performance evaluation of the MINIMET air-sea interactions buoy. *Conference and Exposition on Marine Data Systems, Proceedings.* New Orleans, Louisiana, April 26–28, pp. 69–75.

Katsaros, K. B., and J. E. DeVault, 1986. On irradiance measurement errors at sea due to tilt of pyranometers. *Journal of Atmospheric and Oceanic Technology*, **3**, 740–745.

Table 1: Hippy 120-B Specifications

Variable	Range	Accuracy	Zero Offset	Noise
Pitch	-90 to 90 deg	<0.5%	<0.5 deg	<0.05 deg
Roll	-90 to 90 deg	<0.5%	<0.5 deg	<0.05 deg
Heave	-10 to 10 m	<1.5%	<0.05 m	< 0.03 m
Acceleration	-10 to 10 m/s^2	<1.5%	<1.0 m/s^2	–

Table 2: Pyranometer Specifications

	Eppley 8-48	Hollis MR-5
Serial Number	10420	5-192
Sensitivity ($uV/(W/m^2)$)	11	72
Linearity with Temperature (-20 to 40°C)	1.5%	1.5%
Linearity with Intensity (Spectral range 0–1400 W/m^2)	1%	1%
Cosine Response	1.5% (0–80 deg)	2% (0–70 deg) 5% (70–80 deg)
Time Response (sec)	3–4	<1
Calibration Coefficient ($\times$ 1E-6 $VDC/(W/m^2)$)	10.45	71.71
Gain	267.0	41.0

Table 3: Summary of Data Files

File Name (YYMMDDHH)	Location of Buoy
89011718	Ship Deck
89011719	Partially Deployed
89011720	Deployed
89011721	Deployed
89011722	Deployed
89011723	Deployed
89011800	Deployed
89011813	Deployed
89011815	Ship Deck
89011816	Ship Deck

where: YY = Year
MM = Month
DD = Day
HH = Hour (UTC)

Table 4: Variable Statistics — 17 JAN 89 – 18 UTC

Variable	Minimum	Maximum	Mean	Standard Deviation	Variance
Pitch deg)	34.125	43.267	38.869	1.523	2.318
Roll (deg)	-37.243	-29.446	-33.368	1.249	1.561
Heave (m)	-10.000	1.122	-1.317	3.037	9.224
Accel (m/s^2)	-1.248	2.010	0.403	0.378	0.143
Eppley (W/m^2)	112.180	748.347	236.062	189.857	36045.860
Hollis (W/m^2)	67.004	869.695	235.999	232.434	54025.620

Table 5: Variable Statistics — 17 JAN 89 – 19 UTC

Variable	Minimum	Maximum	Mean	Standard Deviation	Variance
Pitch (deg)	-6.742	19.050	4.887	3.574	12.773
Roll (deg)	-18.844	6.823	-3.930	3.444	11.862
Heave (m)	-10.000	9.988	-0.999	3.428	11.753
Accel (m/s^2)	-4.042	5.484	0.403	1.268	1.607
Eppley (W/m^2)	285.648	417.540	348.884	30.884	953.851
Hollis (W/m^2)	67.685	531.953	321.455	66.934	4480.172

Table 6: Variable Statistics — 17 JAN 89 – 20 UTC

Variable	Minimum	Maximum	Mean	Standard Deviation	Variance
Pitch (deg)	-3.991	14.454	3.059	1.901	3.613
Roll (deg)	-9.718	6.488	-0.991	2.035	4.142
Heave (m)	-10.000	9.922	-0.921	3.445	11.867
Accel (m/s^2)	-2.680	6.052	0.402	1.217	1.480
Eppley (W/m^2)	121.499	154.114	136.293	6.675	44.558
Hollis (W/m^2)	122.104	161.218	137.956	6.510	42.384

Table 7: Variable Statistics — 17 JAN 89 – 21 UTC

Variable	Minimum	Maximum	Mean	Standard Deviation	Variance
Pitch (deg)	-4.508	16.690	3.387	2.047	4.188
Roll (deg)	-20.892	5.428	-2.051	2.241	5.023
Heave (m)	-10.000	9.992	-0.925	3.436	11.805
Accel (m/s^2)	-3.158	6.104	0.400	1.184	1.402
Eppley (W/m^2)	35.124	63.079	46.266	4.878	23.798
Hollis (W/m^2)	35.033	78.228	45.175	5.075	25.758

Table 8: Variable Statistics — 17 JAN 89 – 22 UTC

Variable	Minimum	Maximum	Mean	Standard Deviation	Variance
Pitch (deg)	-4.566	13.238	2.620	2.115	4.474
Roll (deg)	-15.581	7.181	-1.859	2.199	4.836
Heave (m)	-10.000	9.618	-0.967	3.458	11.961
Accel (m/s^2)	-3.120	5.584	0.402	1.233	1.521
Eppley (W/m^2)	7.168	18.279	13.371	0.829	0.687
Hollis (W/m^2)	4.081	15.986	11.542	0.758	0.574

Table 9: Variable Statistics — 17 JAN 89 – 23 UTC

Variable	Minimum	Maximum	Mean	Standard Deviation	Variance
Pitch (deg)	-7.389	13.332	2.397	2.029	4.117
Roll (deg)	-15.855	7.077	-1.661	2.324	5.401
Heave (m)	-10.000	9.864	-0.953	3.417	11.677
Accel (m/s^2)	-3.904	6.440	0.407	1.252	1.568
Eppley (W/m^2)	6.810	17.920	13.107	0.863	0.744
Hollis (W/m^2)	4.422	15.986	11.249	0.809	0.654

Table 10: Variable Statistics — 18 JAN 89 – 00 UTC

Variable	Minimum	Maximum	Mean	Standard Deviation	Variance
Pitch (deg)	-3.899	15.129	3.009	2.232	4.982
Roll (deg)	-20.573	7.008	-2.325	2.523	6.365
Heave (m)	-10.000	9.692	-0.877	3.430	11.762
Accel (m/s^2)	-3.126	5.212	0.386	1.224	1.498
Eppley (W/m^2)	6.810	17.562	13.249	0.842	0.709
Hollis (W/m^2)	3.061	14.965	11.046	0.786	0.618

Table 11: Variable Statistics — 18 JAN 89 — 13 UTC

Variable	Minimum	Maximum	Mean	Standard Deviation	Variance
Pitch (deg)	-0.195	8.882	3.118	1.095	1.198
Roll (deg)	-4.003	4.922	-0.000	1.029	1.059
Heave (deg)	-10.000	10.000	-0.383	3.503	12.270
Accel (m/s^2)	-1.218	2.624	0.349	0.505	0.255
Eppley (W/m^2)	293.174	372.381	324.844	15.802	249.702
Hollis (W/m^2)	234.345	382.639	323.280	20.041	401.661

Table 12: Variable Statistics — 18 JAN 89 – 15 UTC

Variable	Minimum	Maximum	Mean	Standard Deviation	Variance
Pitch (deg)	38.682	48.677	43.524	1.489	2.218
Roll (deg)	-31.534	-23.753	-28.143	1.276	1.627
Heave (m)	-10.000	9.922	-0.931	3.332	11.102
Accel (m/s^2)	-0.610	1.518	0.343	0.316	0.100
Eppley (W/m^2)	93.543	936.150	289.404	271.152	73523.530
Hollis (W/m^2)	74.147	1149.277	297.424	343.831	118219.900

Table 13: Variable Statistics — 18 JAN 89 – 16 UTC

Variable	Minimum	Maximum	Mean	Standard Deviation	Variance
Pitch (deg)	40.421	48.108	44.278	1.372	1.881
Roll (deg)	-30.637	-23.254	-26.899	1.205	1.452
Heave (m)	-10.000	9.924	-0.925	3.301	10.895
Accel (m/s^2)	0.000	0.704	0.342	0.100	0.010
Eppley (W/m^2)	310.736	469.509	411.879	31.927	1019.343
Hollis (W/m^2)	313.594	546.238	450.222	39.112	1529.726

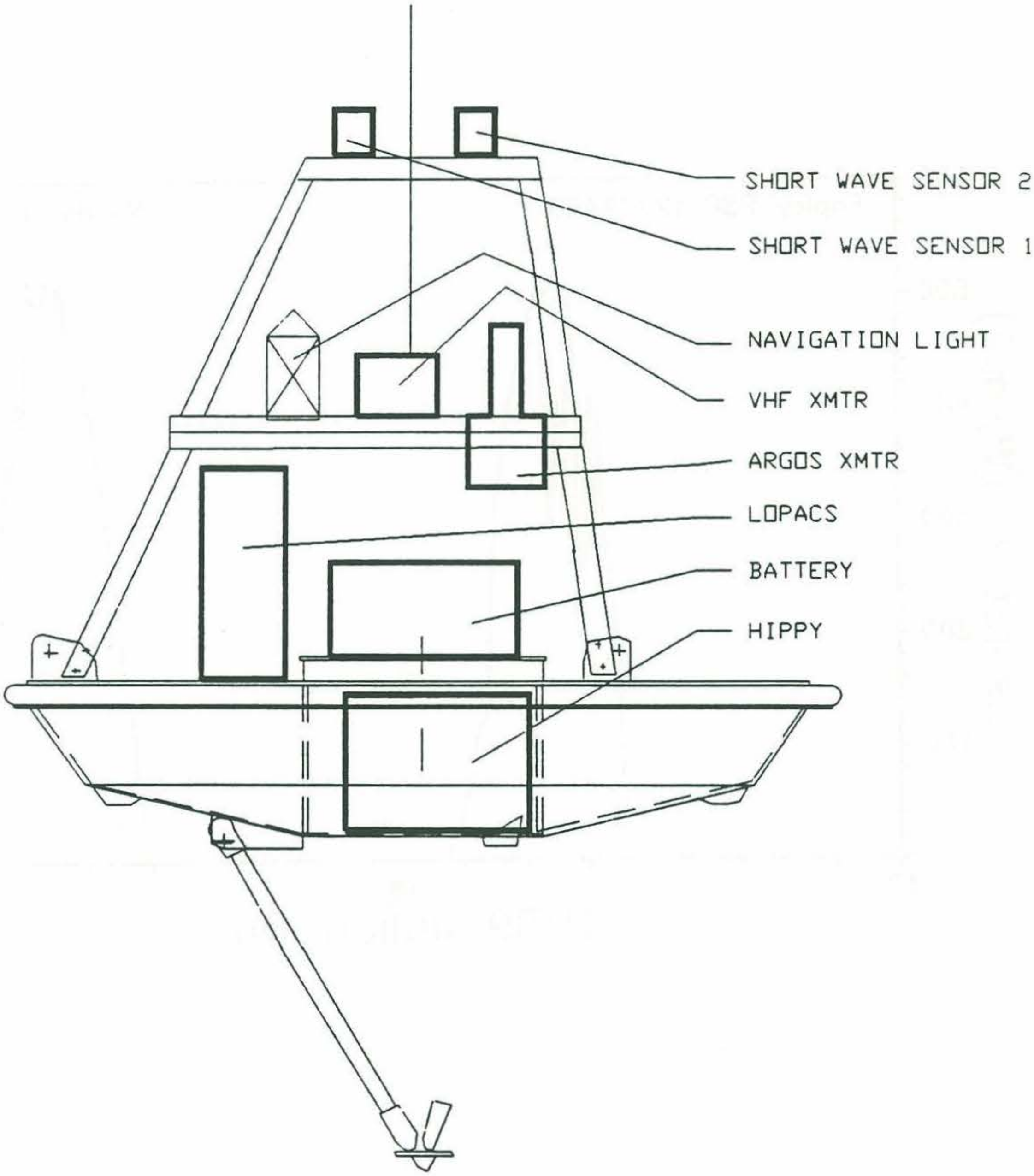

Figure 1: Line drawing of IMET Test Buoy.

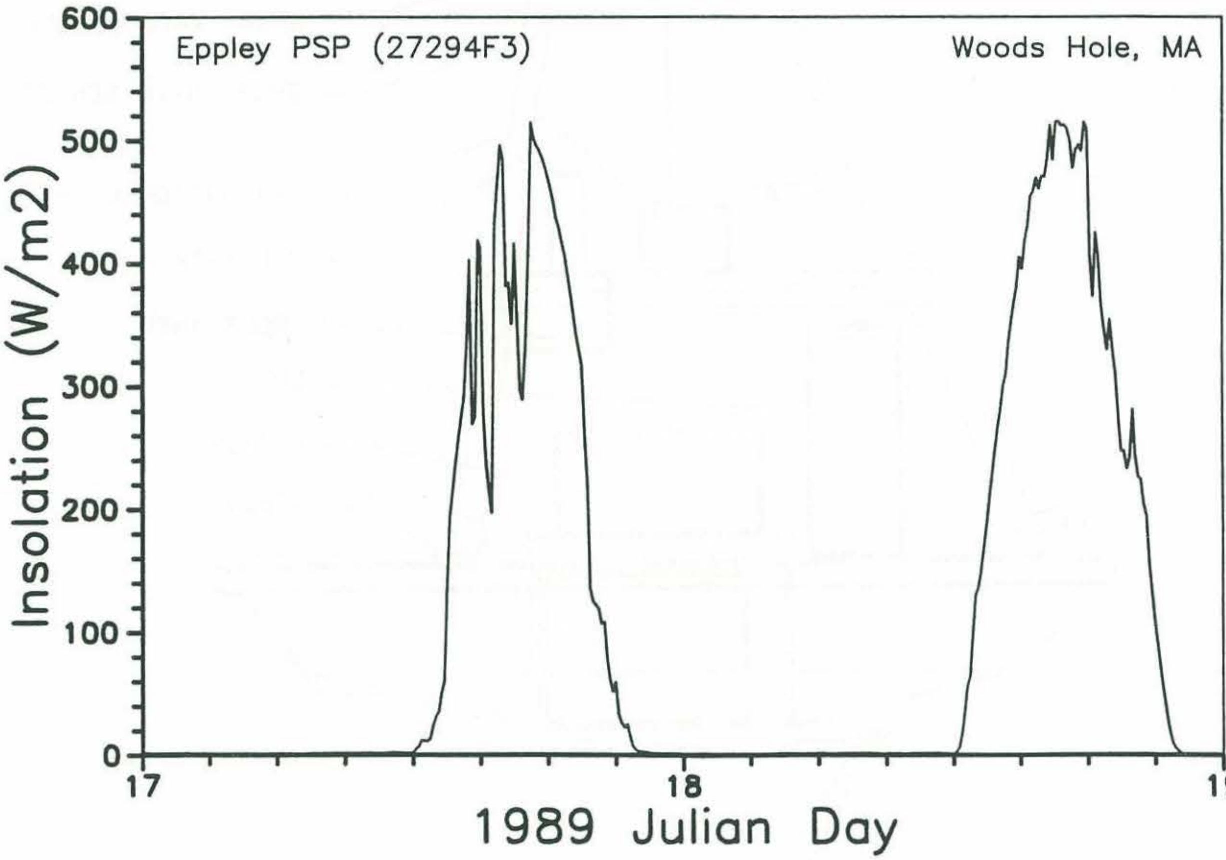

Figure 2: Insolation values for 17 and 18 January observed at Woods Hole, Massachusetts, by an Eppley Precision Spectral Pyranometer. WHOI Buoy Farm is approximately 40 km away.

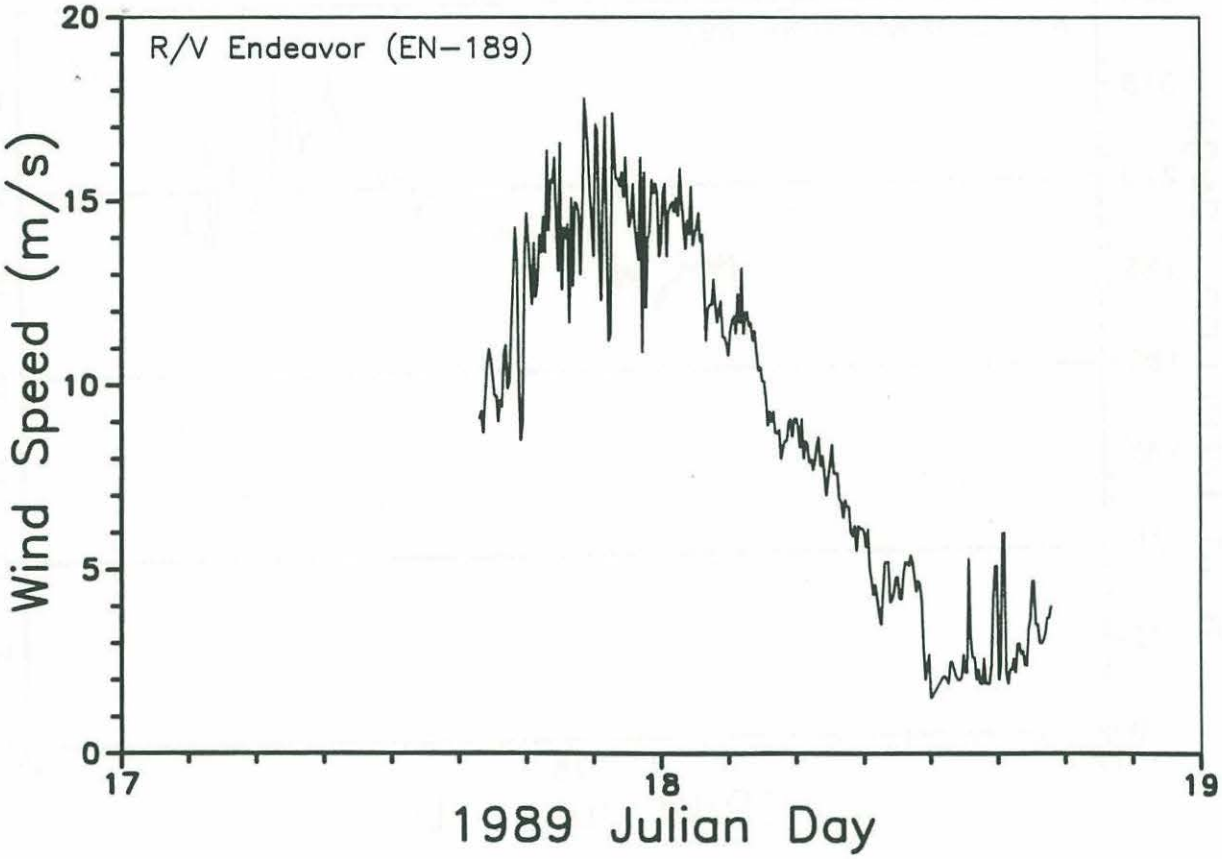

Figure 3: Wind speeds recorded by the *R/V Endeavor* during cruise EN-189. Sampling rate is 5 minutes.

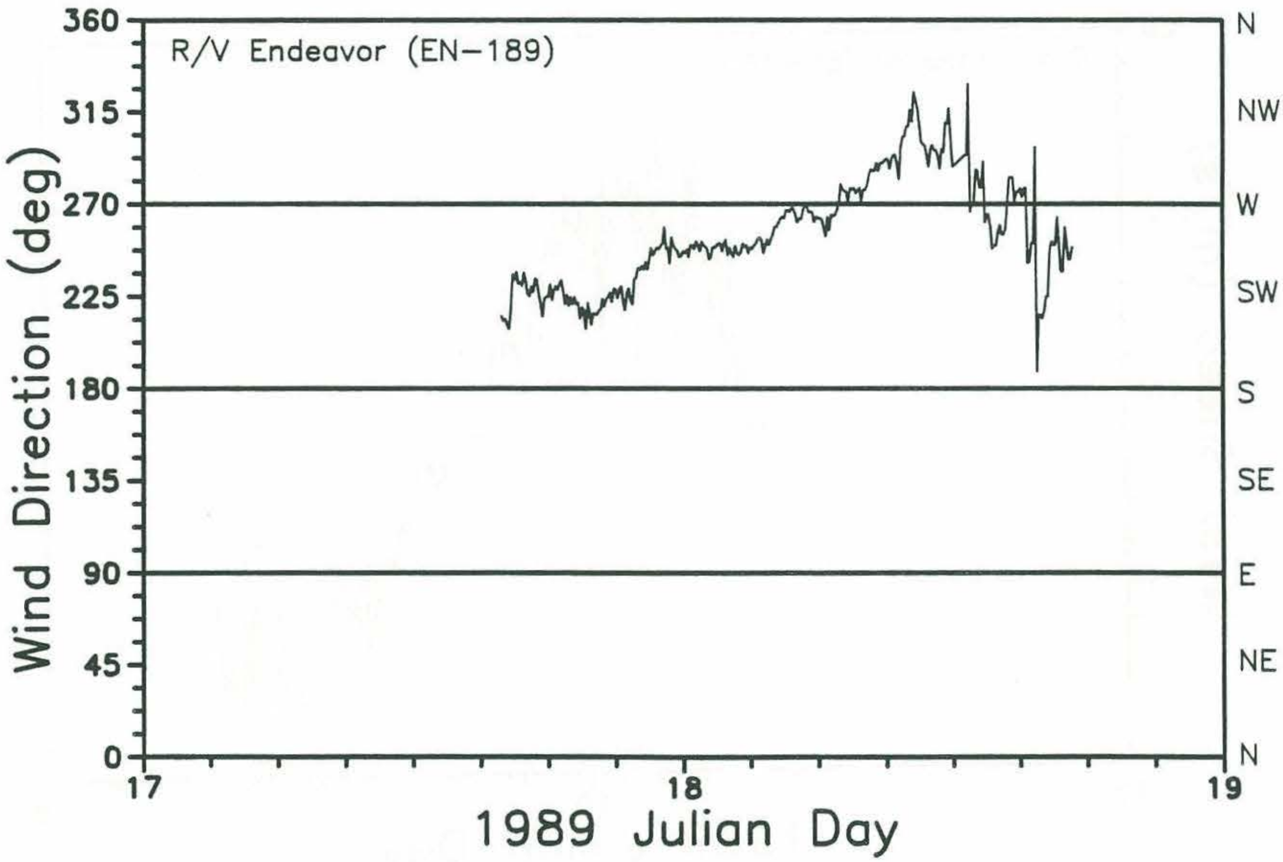

Figure 4: Wind direction recorded by the *R/V Endeavor* during cruise EN-189. Sampling rate is 5 minutes.

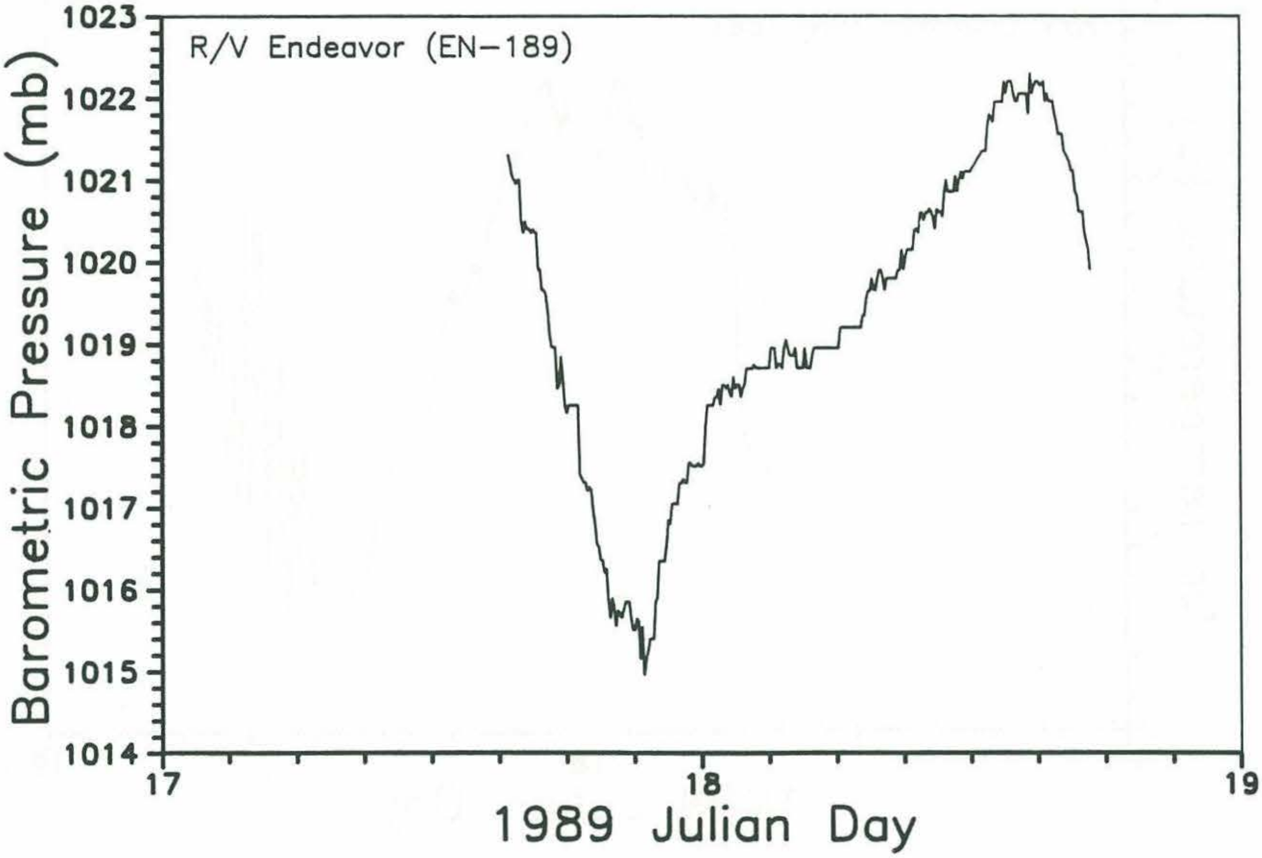

Figure 5: Barometric pressure recorded by the *R/V Endeavor* during cruise EN-189. Sampling rate is 5 minutes.

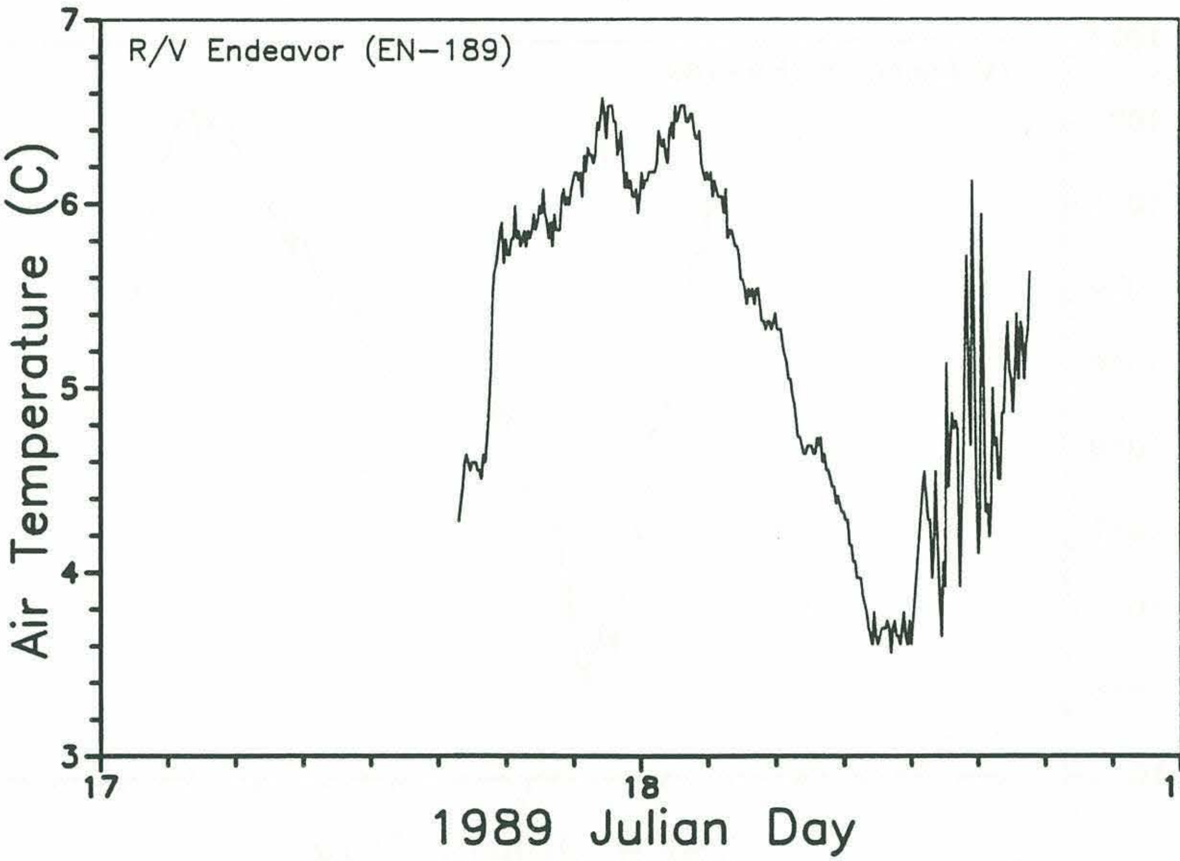

Figure 6: Air temperature recorded by the *R/V Endeavor* during cruise EN-189. Sampling rate is 5 minutes.

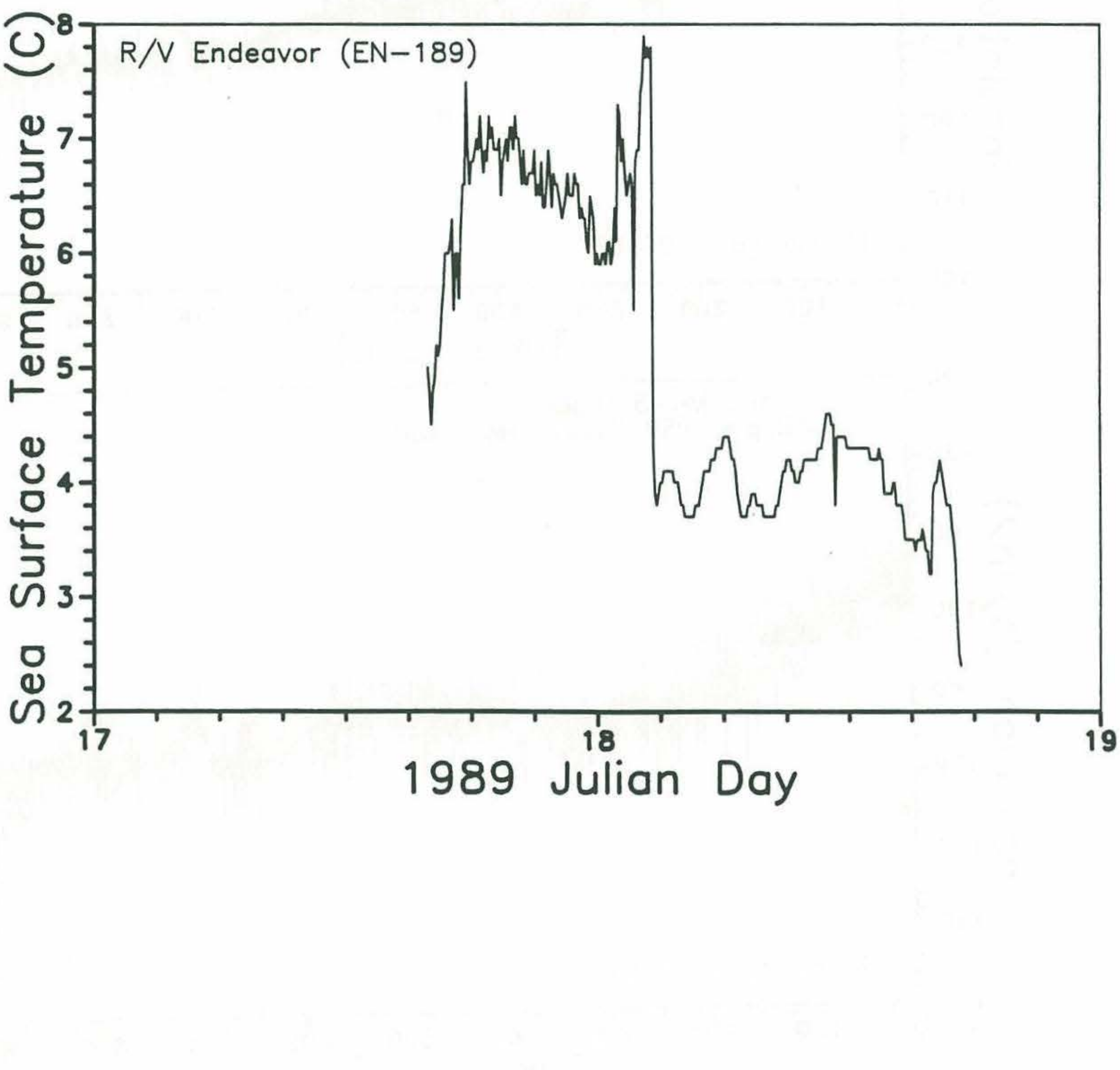

Figure 7: Sea surface temperature recorded by the *R/V Endeavor* during cruise EN-189. Sampling rate is 5 minutes.

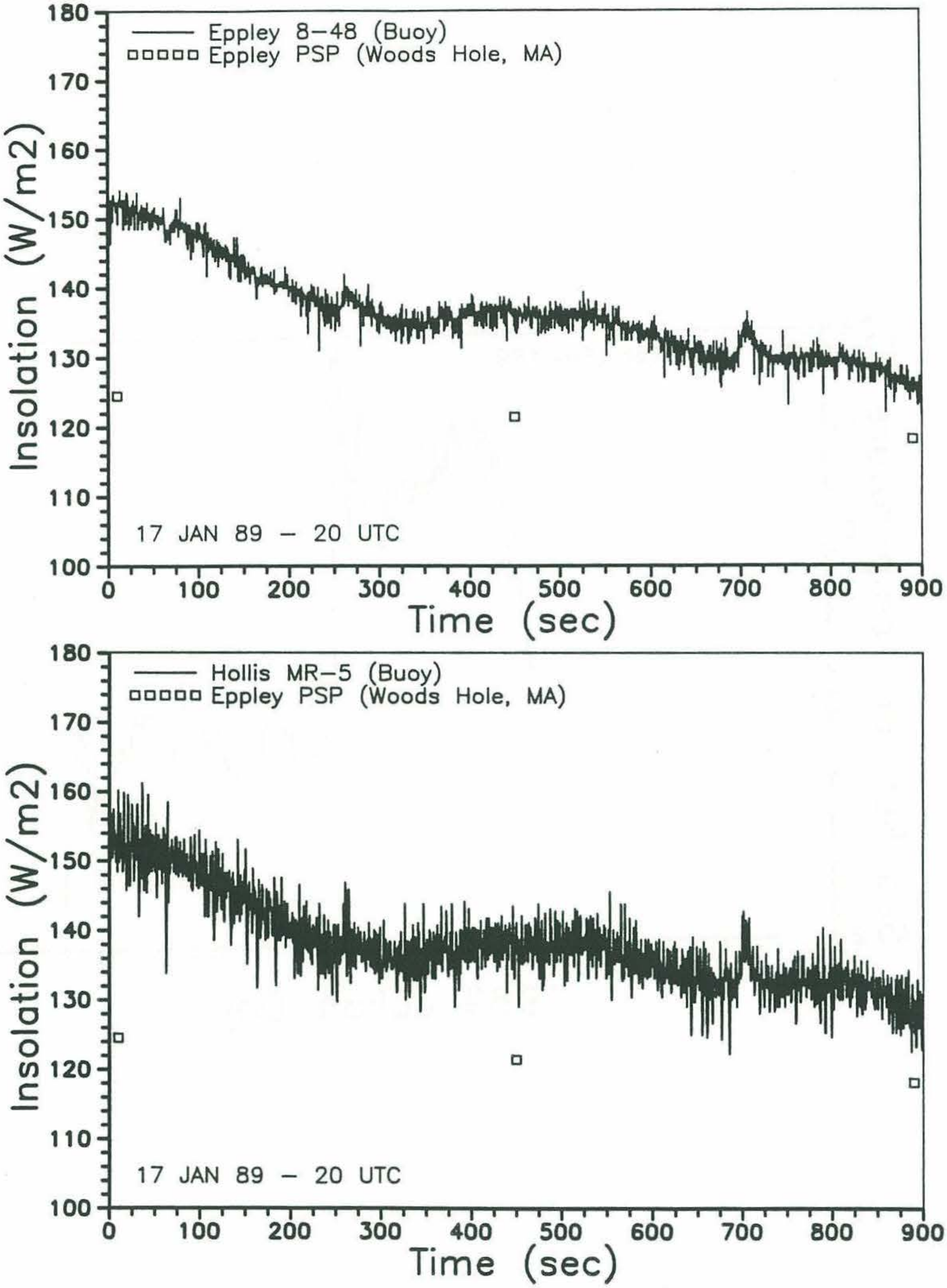

Figure 8: Insolation values recorded on test buoy on 17 January 1989 at 20 UTC. Sampling rate for insolation on buoy is 4 Hz. Insolation values from Woods Hole are 7.5 minute averages.

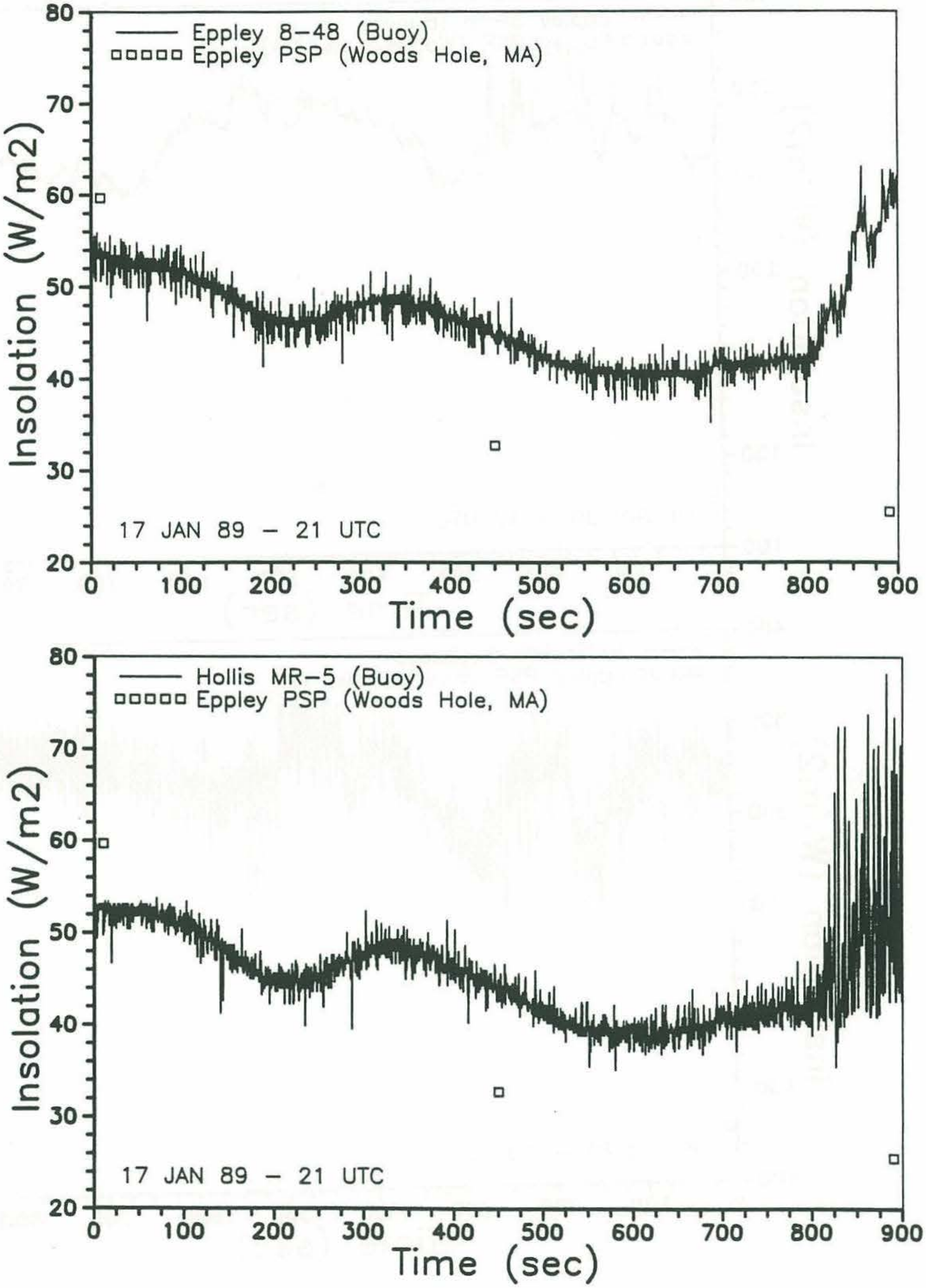

Figure 9: Insolation values recorded on test buoy on 17 January 1889 at 21 UTC.

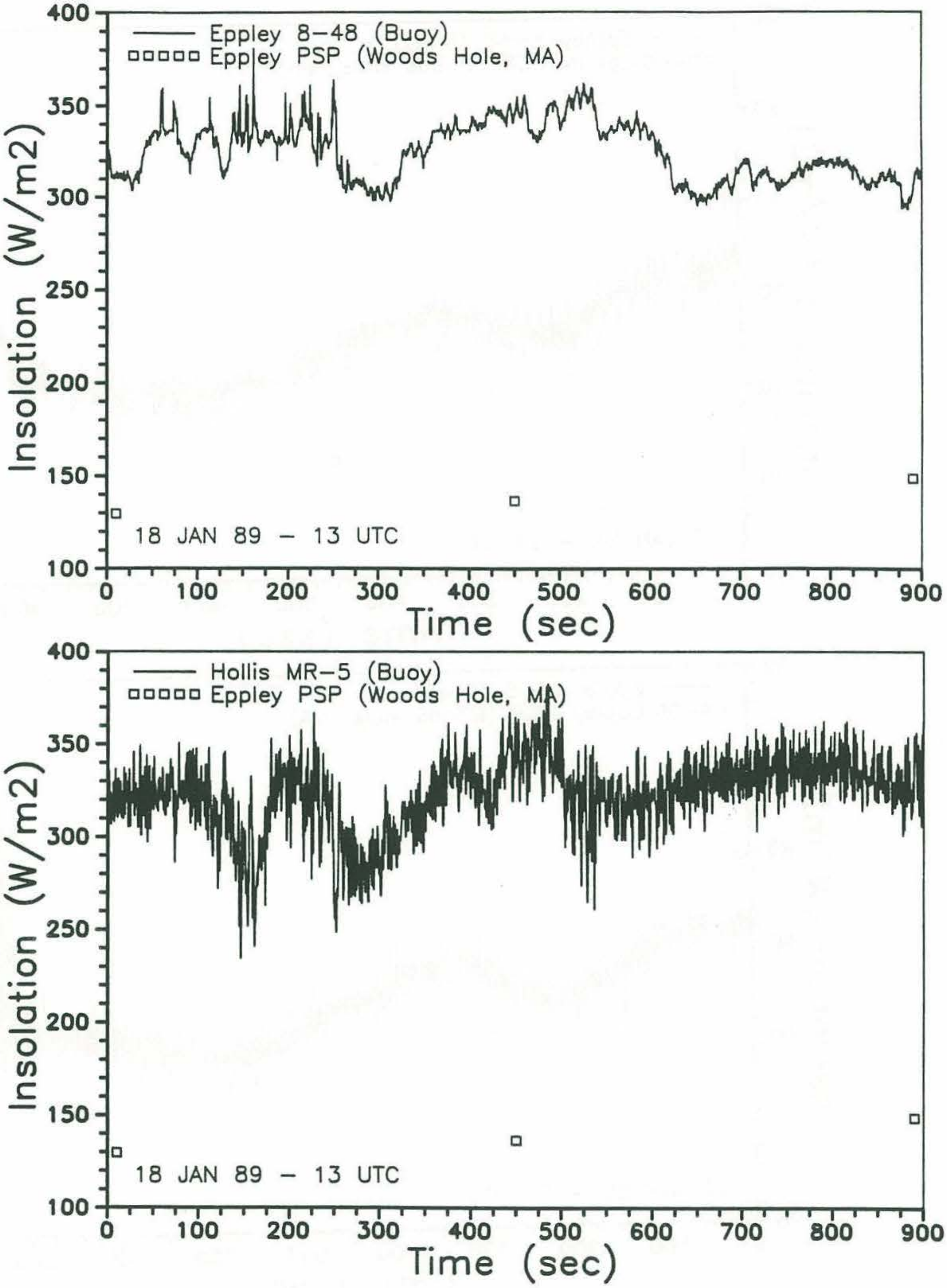

Figure 10: Insolation values recorded on test buoy on 18 January 1989 at 13 UTC.

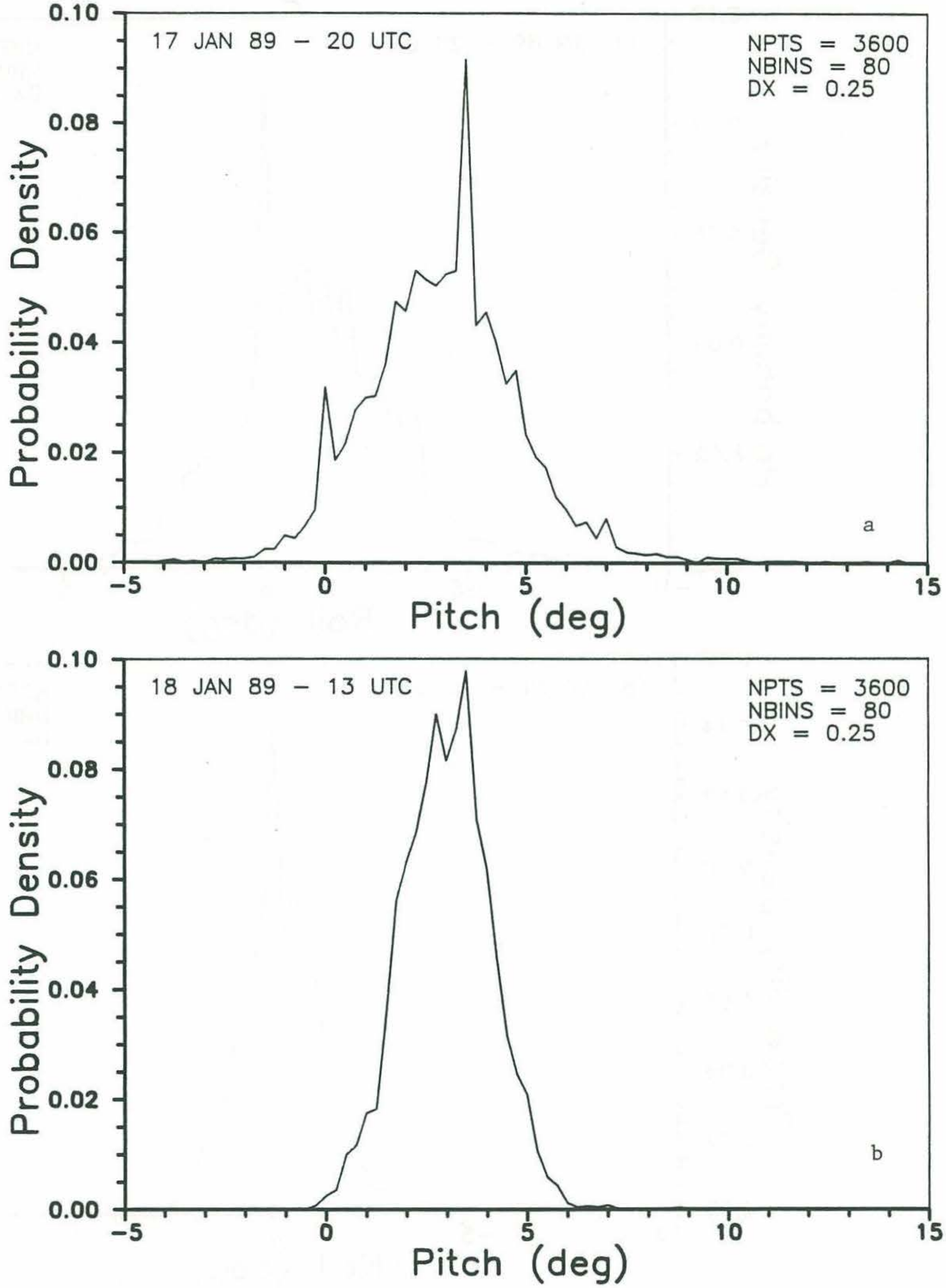

Figure 11: Probability density of buoy pitch for (a) 20 UTC on 17 January and (b) 13 UTC on 18 January.

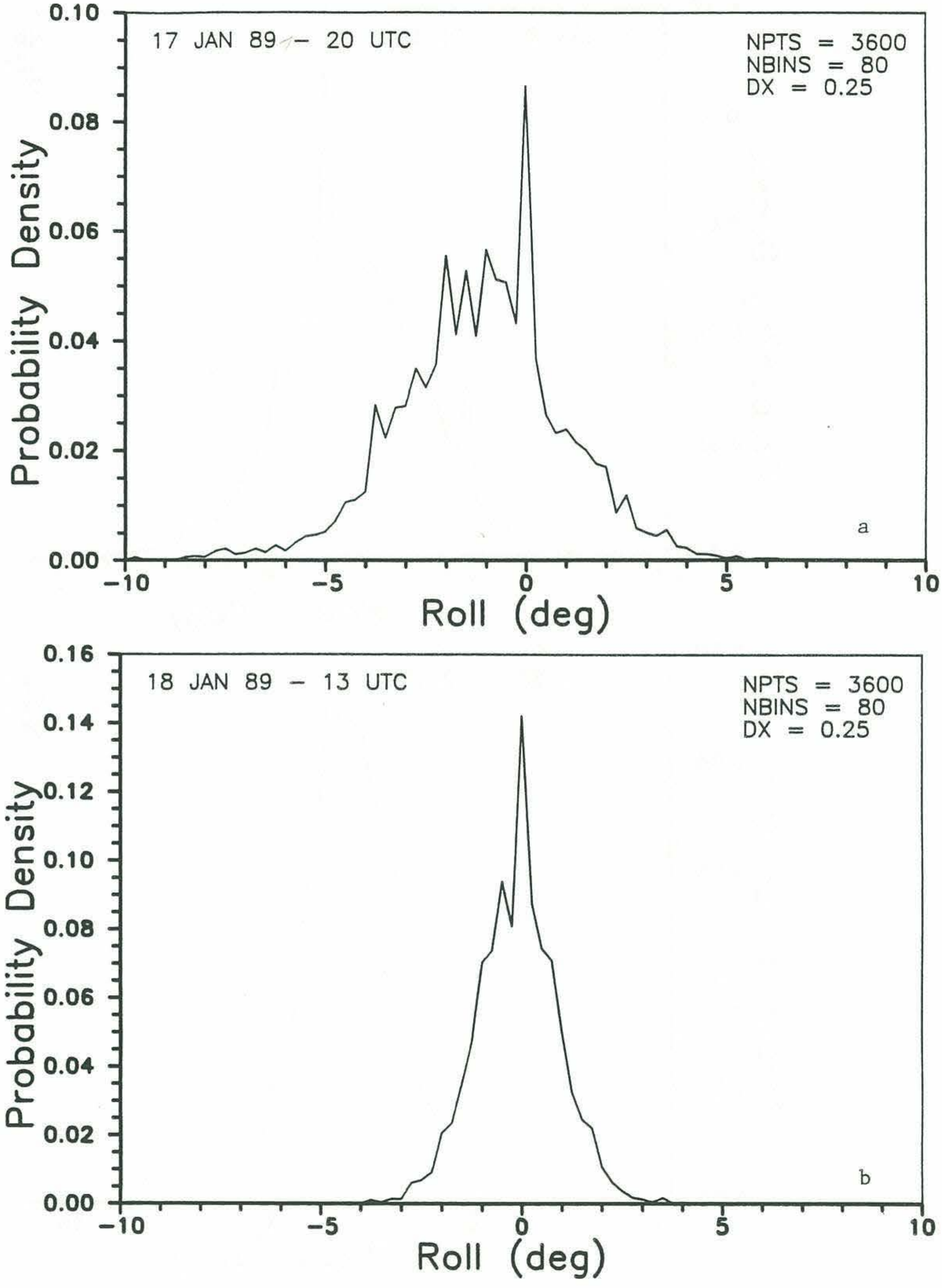

Figure 12: Probability density of buoy roll for (a) 20 UTC on 17 January and (b) 13 UTC on 18 January.

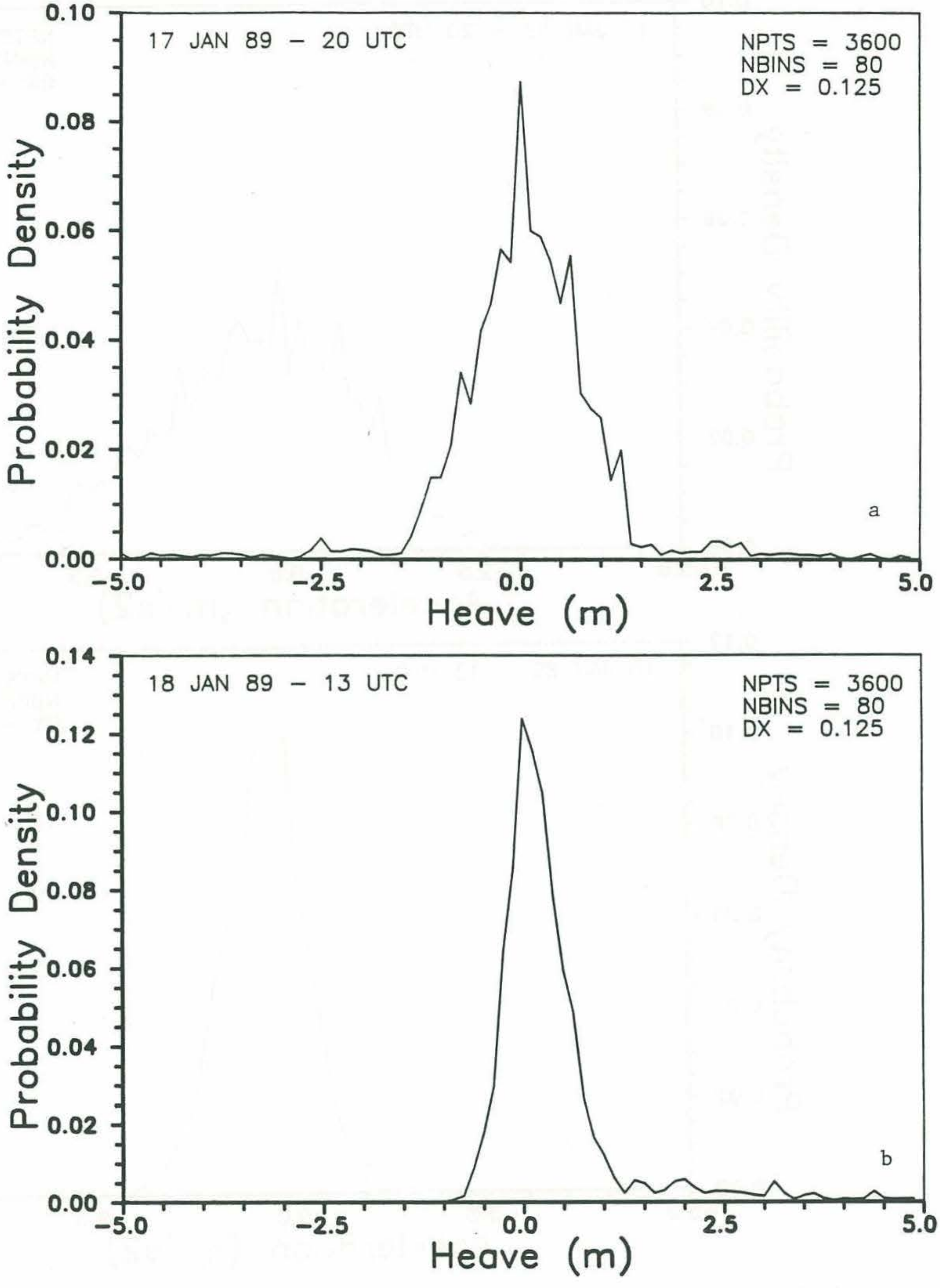

Figure 13: Probability density of buoy heave for (a) 20 UTC on 17 January and (b) 13 UTC on 18 January.

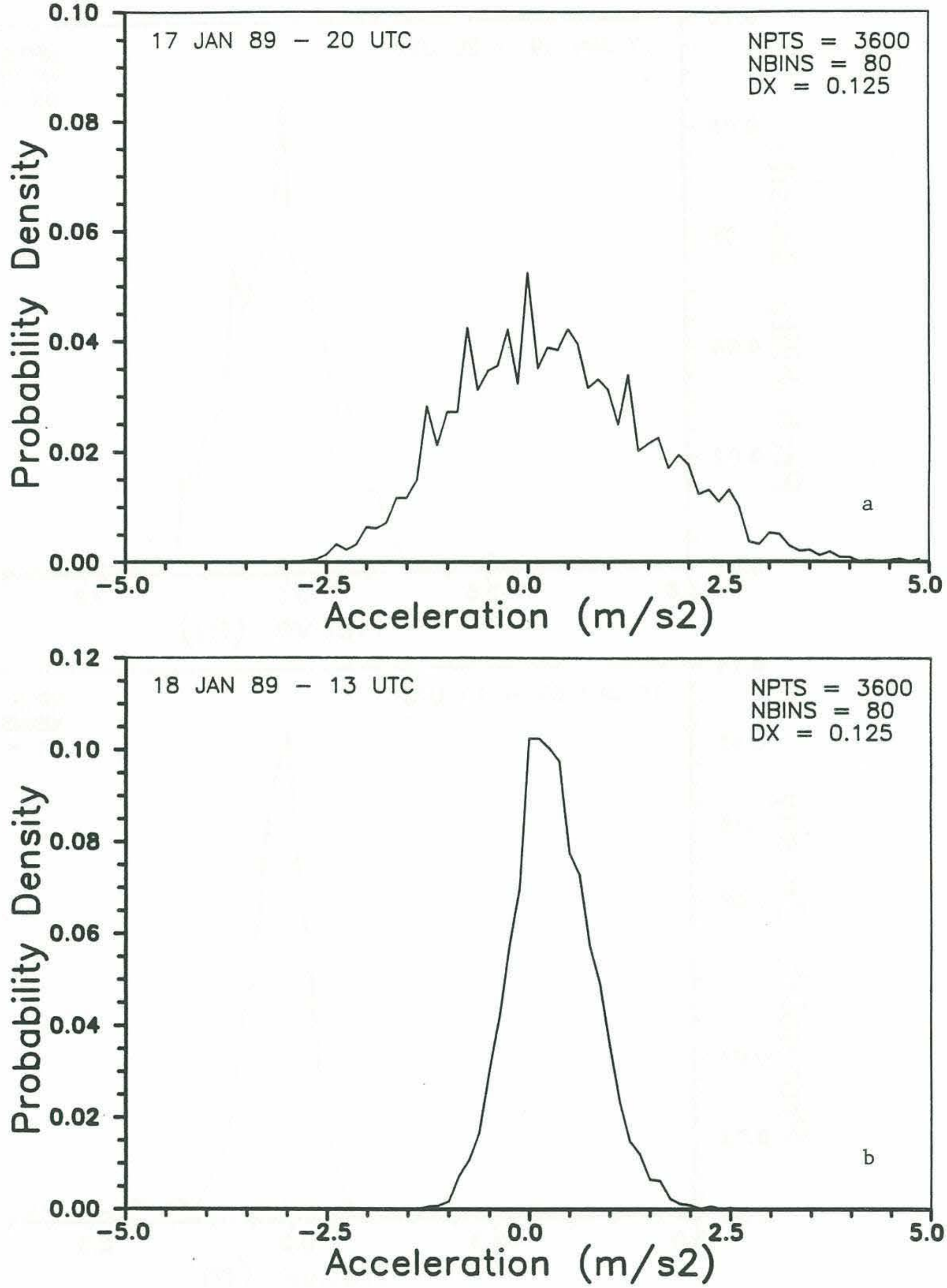

Figure 14: Probability density of buoy vertical acceleration for (a) 20 UTC on 17 January and (b) 13 UTC on 18 January.

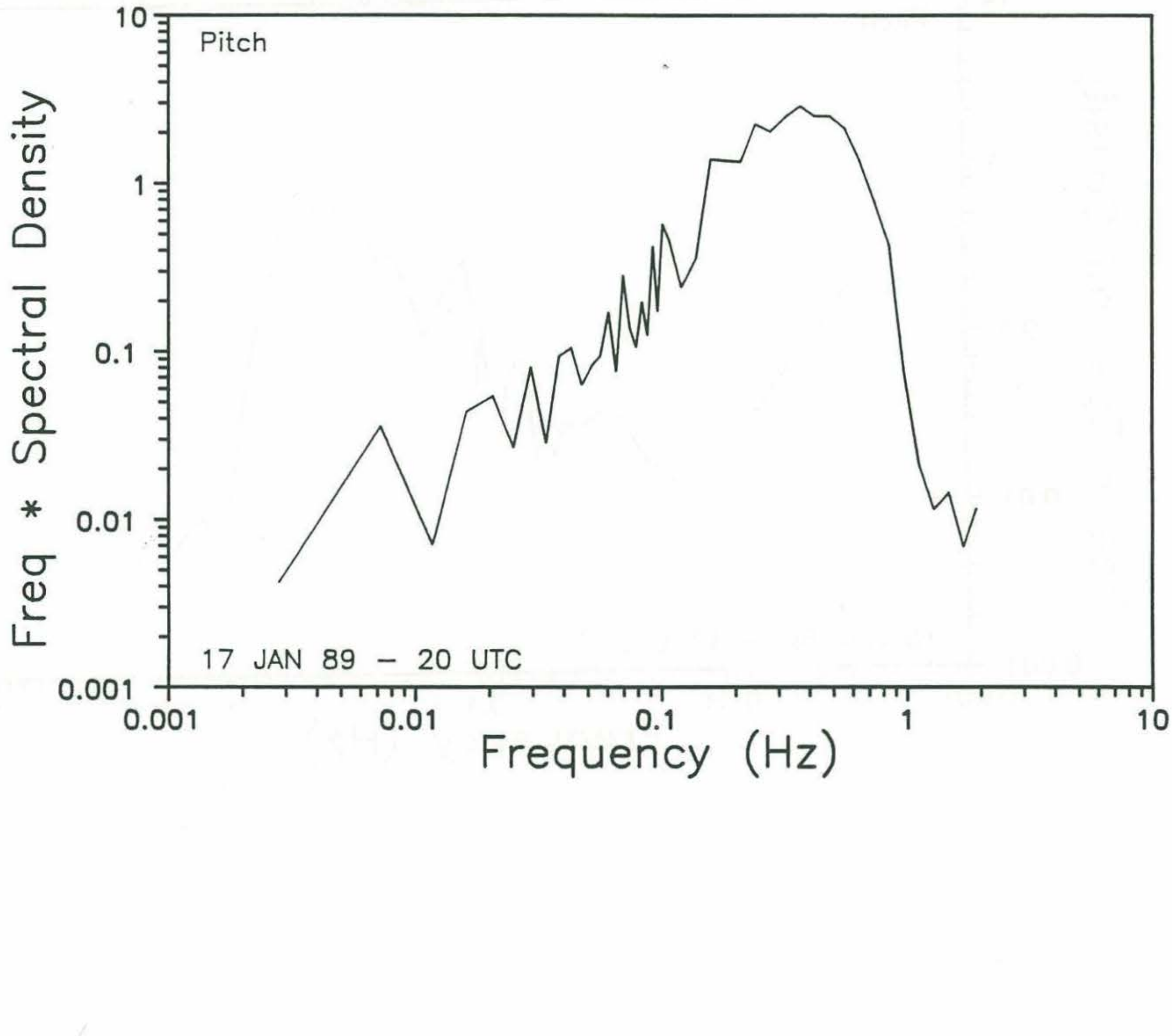

Figure 15: Spectra of buoy pitch for 20 UTC on 17 January.

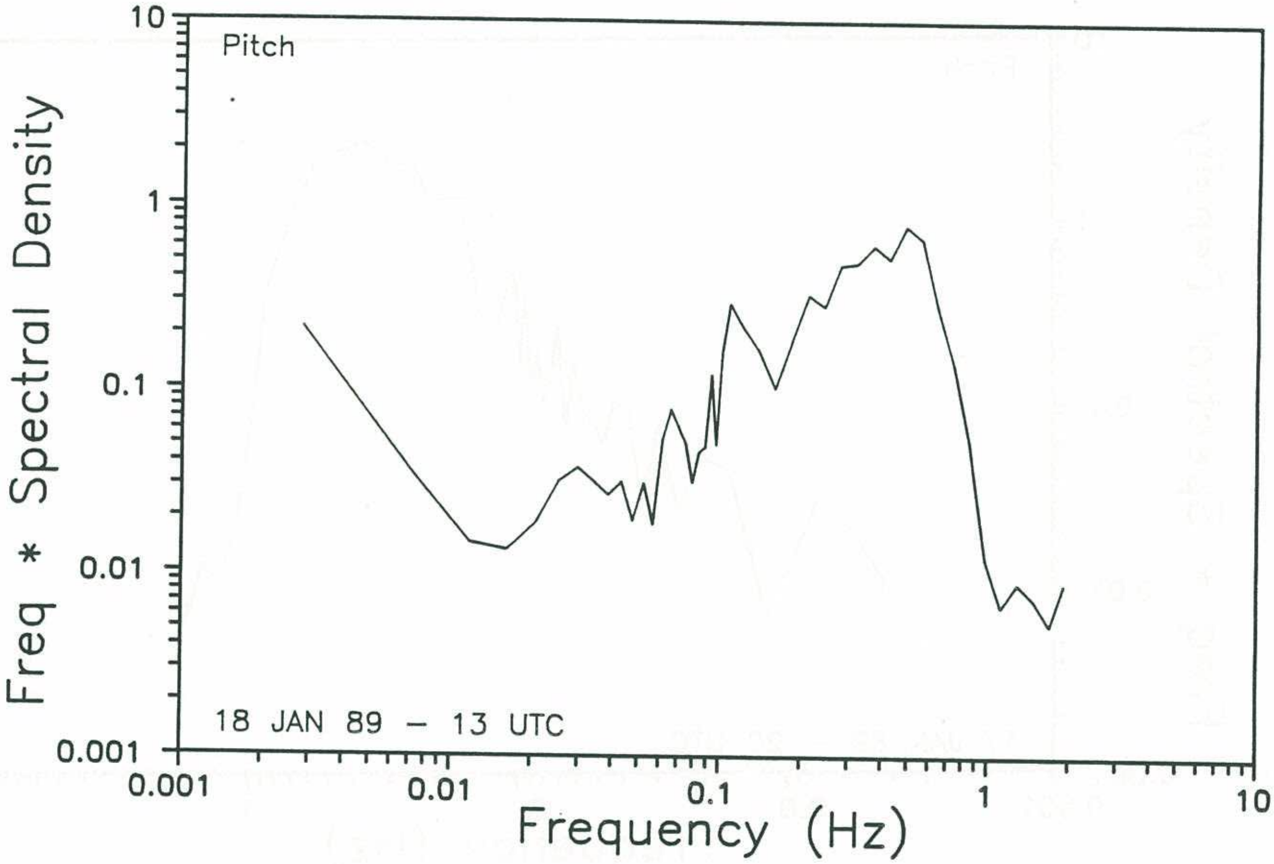

Figure 16: Spectra of buoy pitch for 13 UTC on 18 January.

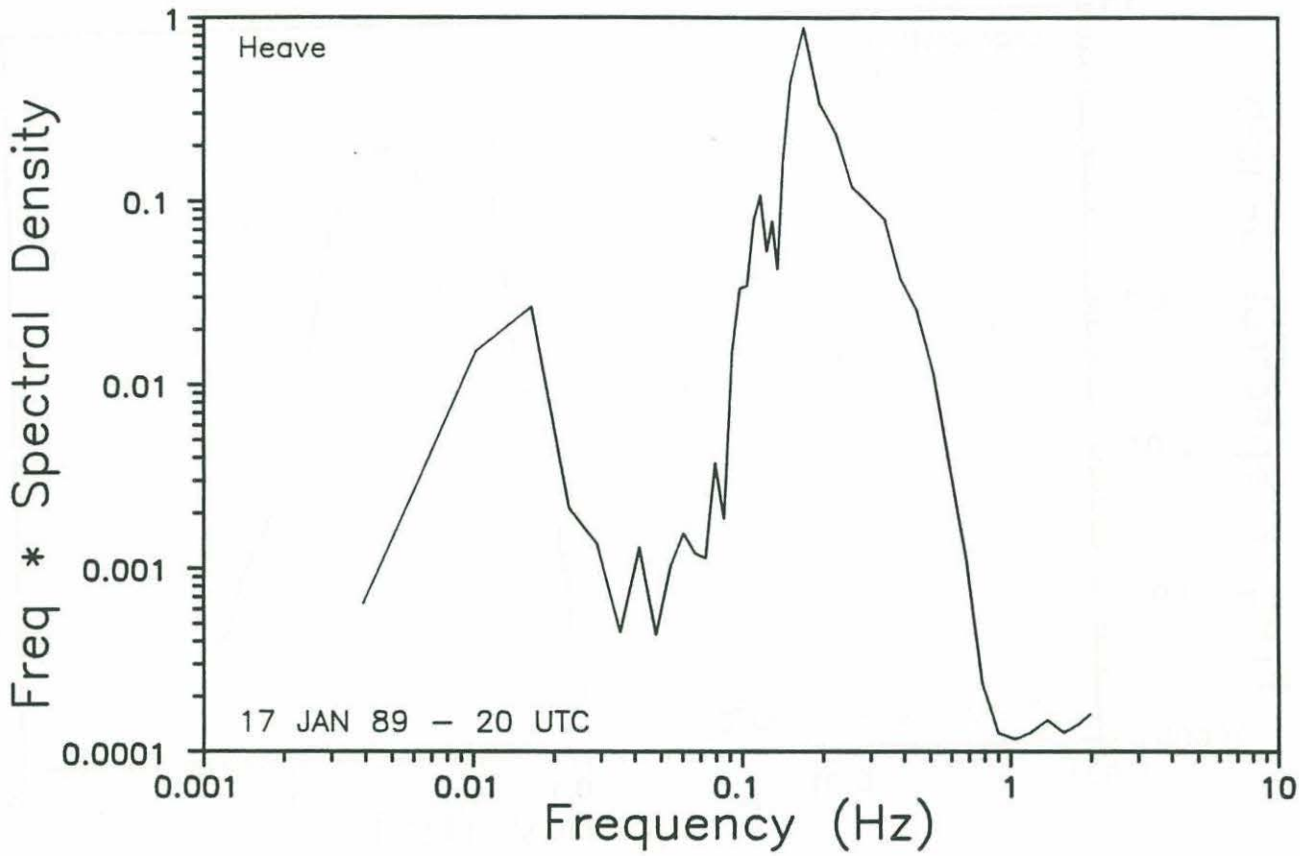

Figure 17: Spectra of buoy heave for 20 UTC on 17 January.

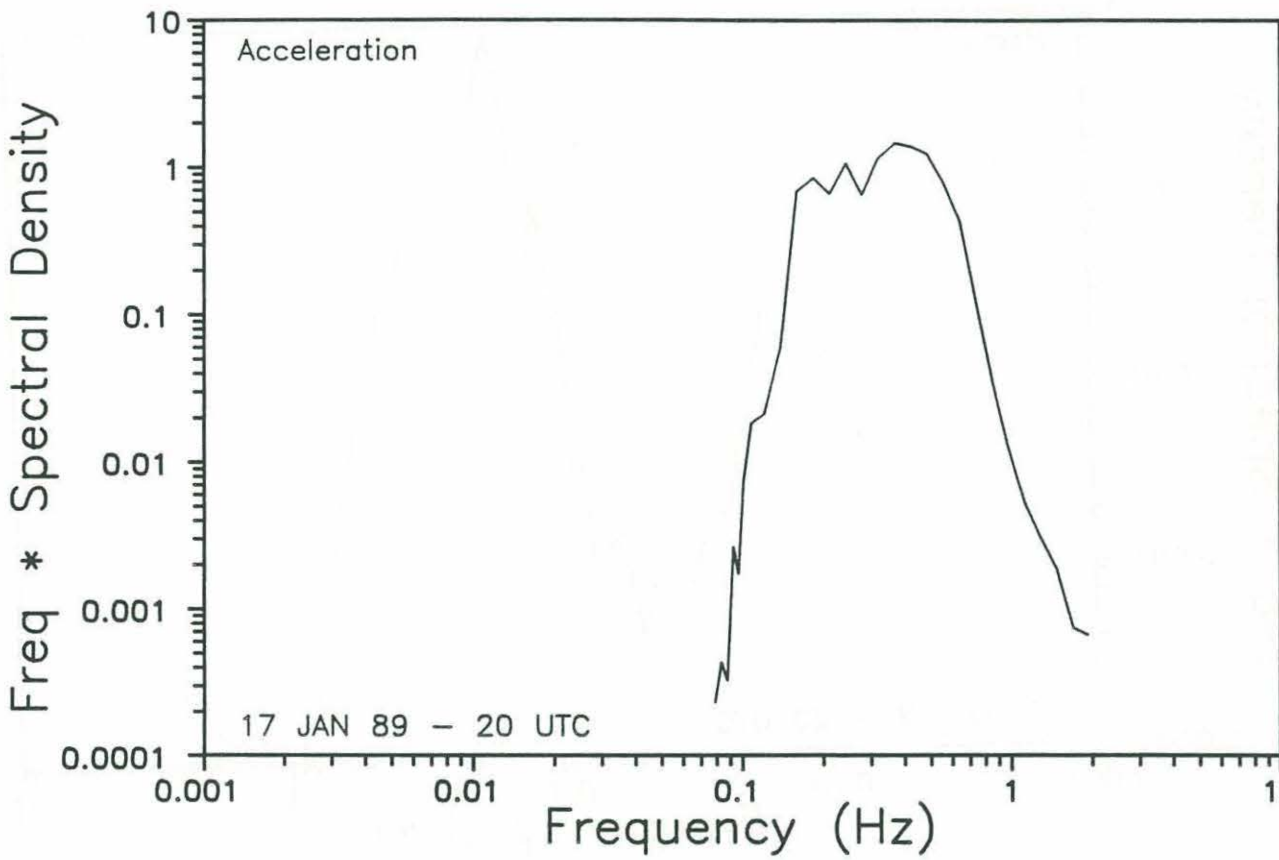

Figure 18: Spectra of buoy acceleration for 20 UTC on 17 January.

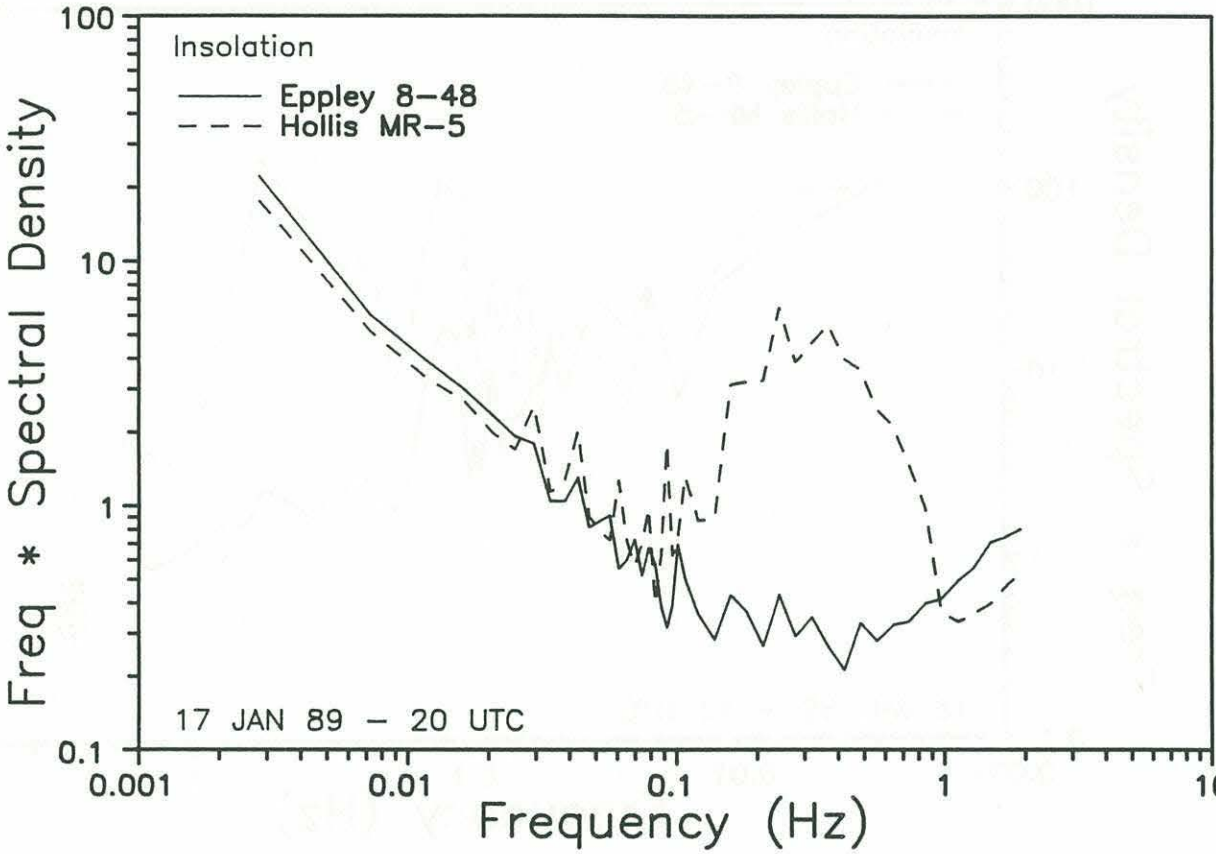

Figure 19: Spectra of insolation recorded by Eppley 8-48 (solid) and Hollis MR-5 (dashed) for 20 UTC on 17 January.

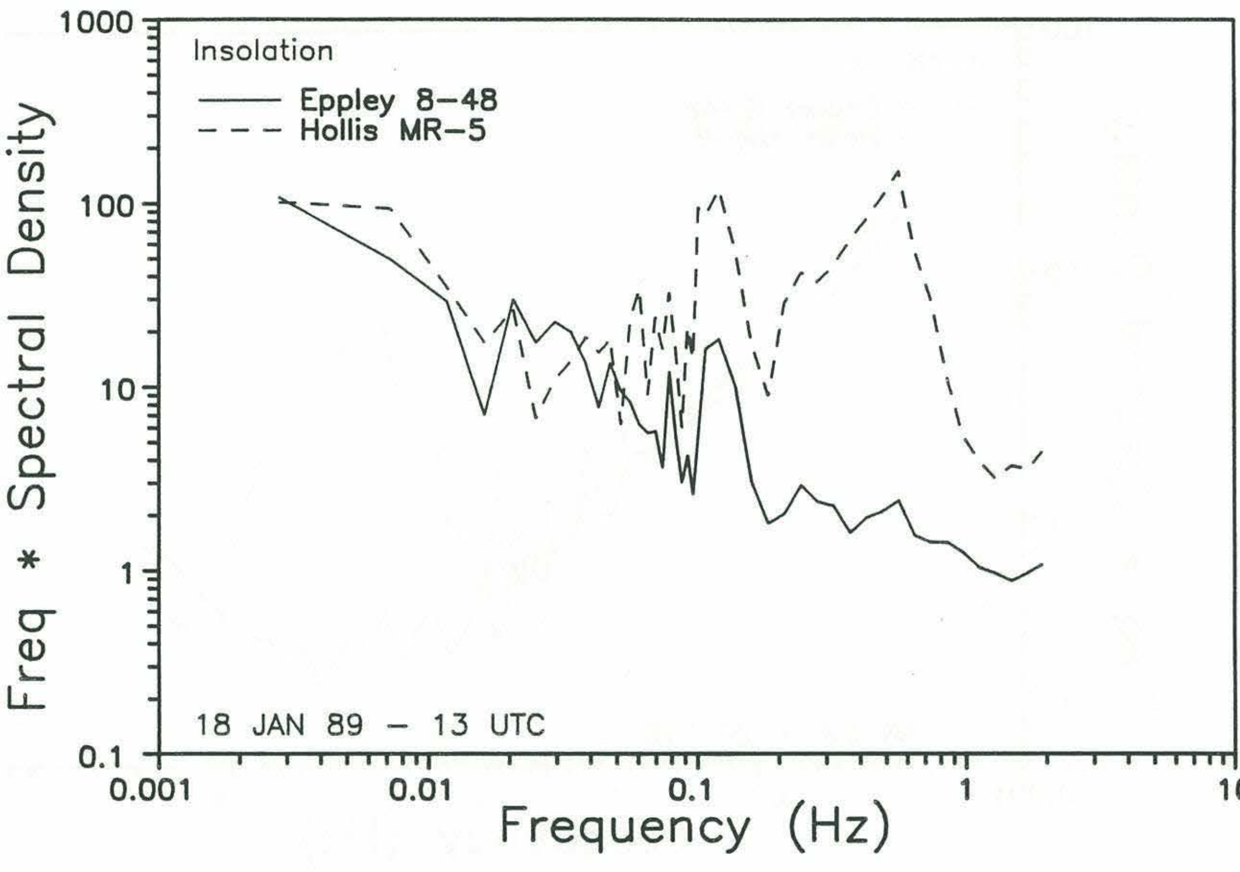

Figure 20: Spectra of insolation recorded by Eppley 8-48 (solid) and Hollis MR-5 (dashed) for 13 UTC on 18 January.

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16. Abstract (Limit: 200 words)

Data are analyzed from a test buoy equipped with a motion sensor (Hippy) and two different pyranometers in order to understand and quantify motion induced errors in meteorological data. The Hippy measures pitch, roll, heave and acceleration of the buoy. Probability density functions and spectra of buoy motion and insolation are constructed and discussed.

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